AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR016056

Uncertainty in modeled and observed climate change impacts on American Midwest hydrology

Jonathan M. Winter[1], **Pat J.-F. Yeh**[2], **Xiaojing Fu**[3], **and Elfatih A.B. Eltahir**[3]

[1]Center for Climate Systems Research, Columbia University, New York, New York, USA, [2]Department of Civil and Environmental Engineering, National University of Singapore, Singapore, Singapore, [3]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Key Points:

- Models show contradictory climate change impacts on the hydrologic cycle
- No trends are found in hydrologic cycle or surface temperature observations
- Climate change impacts on American Midwest soil moisture are uncertain

Correspondence to:
J. M. Winter,
jwinter@dartmouth.edu

Citation:
Winter, J. M., P. J.-F. Yeh, X. Fu, and E. A. B. Eltahir (2015), Uncertainty in modeled and observed climate change impacts on American Midwest hydrology, *Water Resour. Res.*, *51*, 3635–3646, doi:10.1002/2014WR016056.

Received 27 JUN 2014
Accepted 22 APR 2015
Accepted article online
Published online 22 MAY 2015

Abstract An important potential consequence of climate change is the modification of the water cycle in agricultural areas, such as the American Midwest. Soil moisture is the integrand of the water cycle, reflecting dynamics of precipitation, evapotranspiration, and runoff in space and time, and a key determinant of yield. Here we present projected changes in the hydrologic cycle over a representative area of the American Midwest from regional climate model experiments that sample a range of model configurations. While significant summer soil moisture drying is predicted in some ensemble members, others predict soil moisture wetting, with the sign of soil moisture response strongly influenced by choice of boundary conditions. To resolve the contradictory predictions of soil moisture across ensemble members, we assess an extensive and unique observational data set of the water budget in Illinois. No statistically significant monotonic trends are found in observed soil moisture, precipitation, streamflow, groundwater level, or 2 m air temperature over a recent 26 year period (soil moisture 25 years). Based on this analysis of model simulations and observations, we conclude that the sign of climate change impacts on the regional hydrology of the American Midwest remains uncertain.

1. Introduction

The agricultural output of the Midwestern United States is critical to both the American economy and global food security [*Alston et al.*, 2010]. From 1980 to 2005, the United States experienced over $145 billion in damages due to droughts and heat waves [*Lott and Ross*, 2006], and climate change is anticipated to exacerbate future losses [*Melillo et al.*, 2014]. The American Midwest, and specifically Illinois, offers a remarkable opportunity to evaluate the accuracy of climate model projections due to the availability of comprehensive hydrologic observations collected by the Illinois State Water Survey (ISWS). Extensive previous work has been conducted using the Illinois data on a diversity of topics, including land-atmosphere coupling and precipitation recycling [e.g., *Findell and Eltahir*, 1997; *Salvucci et al.*, 2002; *D'Odorico and Porporato*, 2004; *Kochendorfer and Ramirez*, 2005; *Teuling et al.*, 2005], and terrestrial water storage [e.g., *Yeh and Famiglietti*, 2008, 2009].

Multiple studies have investigated the response of surface (2 m air) temperature and precipitation to climate change across the American Midwest and United States; however, few have examined the response of soil moisture, and still fewer have assessed soil moisture using a combination of model simulations and regional observations. Of the studies that considered soil moisture, several found summer soil moisture drying in the American Midwest under climate change scenarios [*Manabe et al.*, 2004; *Wang*, 2005; *Diffenbaugh and Ashfaq*, 2010]. *Manabe et al.* [2004] used the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model (GCM) forced with the Intergovernmental Panel on Climate Change (IPCC) IS92a scenario and a 4 $\times$ CO_2 scenario, *Wang* [2005] used 15 different GCMs from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) archive, and *Diffenbaugh and Ashfaq* [2010] used an ensemble of Regional Climate Model version 3 (RegCM3) simulations forced with five National Center for Atmospheric Research (NCAR) Community Climate System Model 3 (CCSM) projections. While exact findings vary, the mechanism for summer soil moisture drying was generally increased evapotranspiration, and stable or reduced precipitation. However, other studies found unchanged or increased summer soil moisture across the American Midwest under climate change [*Seneviratne et al.*, 2002; *Mishra et al.*, 2010]. *Seneviratne et al.* [2002] used a series of RegCM3 experiments modifying air temperature, sea surface temperature, and CO_2 concentrations, and *Mishra et al*. [2010] used the Variable Infiltration Capacity (VIC) model forced with three CMIP3 GCMs. Unchanged or increased summer soil moisture resulted from one or more of the following factors: enhanced precipitation, additional infiltration, and strict plant controls on evapotranspiration. Broader evaluations of future drought conditions over the American Midwest are also mixed, and depend on model, time period, drought index, and month of growing season considered [*Sheffield and Wood*, 2008; *Strzepek et al*., 2010; *Patricola and Cook*, 2012]. In this study, we use both modeling and observational approaches to explore the impacts of climate change on the hydrology of the American Midwest, as well as suggest potential causes for disparate results among previous studies.

2. Methods

An ensemble of sixteen RegCM3 [*Pal et al*., 2007] simulations was constructed to assess the historical and future hydroclimatology of the American Midwest. Ensemble members were designed to analyze uncertainty in simulating the hydrologic cycle of the American Midwest. Results from previous numerical experiments showed that RegCM3 is sensitive to convective closure assumption, surface physics scheme, and boundary conditions [*Winter and Eltahir*, 2012]. RegCM3 was run using a combination of surface physics schemes: Integrated Biosphere Simulator (IBIS) and Biosphere-Atmosphere Transfer Scheme 1e (BATS), and convective closure assumptions: Fritsch & Chappell (FC) and Arakawa & Schubert (AS), to evaluate the influence of model physics on projected climate. Additional details on the surface physics schemes and convective closure assumptions can be found in *Winter et al*. [2009], *Grell et al*. [1994], and *Fritsch and Chappell* [1980].

RegCM3 was forced with two sets of GCM boundary conditions: National Center for Atmospheric Research CCSM and Max Planck Institute for Meteorology ECHAM5 (ECHAM) to evaluate the influence of large-scale forcing on projected climate. There are two approaches generally used for choosing GCM boundary conditions to drive regional climate models (RCMs). The first approach is to run a large number of RCM projections treating each GCM large-scale forcing as a credible prediction, a method consistent with examining the full set of simulations from the North American Regional Climate Change Assessment Program [*Mearns et al*., 2013], ENSEMBLES project [*Van der Linden and Mitchell*, 2009], and Coupled Model Intercomparison Project Phase 5 [*Stocker et al*., 2013; *Melillo et al*., 2014]. This approach has the advantages of enabling probabilistic projections of climate and uncertainty analyses, but the disadvantages of being extremely difficult due to the scale of simulations conducted and susceptible to errors in boundary conditions because GCMs are treated equally regardless of performance. The second approach addresses the disadvantages of running a full ensemble, and constrains projections by selecting climate models based on their ability to reproduce one or more facets of observed climate, as in *Hall and Qu* [2006], *Patricola and Cook* [2012], *Quesada et al*. [2012], and *Stegehuis et al*. [2013]. This study does not conform to either of these approaches. Instead, we use two different sets of boundary conditions to illustrate that conclusions about the future of soil moisture in the American Midwest depend to a significant degree on choice of boundary conditions.

In a recent study, *Diffenbaugh and Ashfaq* [2010] forced RegCM3 with CCSM to explore the future of hot extremes in the United States. Over the American Midwest, they found increases in a variety of temperature metrics, as well as a coincident decrease in summer soil moisture. In order to compare our results to *Diffenbaugh and Ashfaq* [2010] we chose boundary conditions from the same model, CCSM, to force half of our RCM simulations. We forced the other half using boundary conditions from ECHAM, which was deemed an alternate valid model choice. ECHAM has a wet bias in contrast to CCSM's dry bias, so by using both GCMs we cover a range of model behavior in simulating precipitation. In addition, ECHAM reproduces observed temperature more accurately than CCSM and simulates the Great Plains low-level jet well [*Patricola and Cook*, 2012]. In the context of this study, any GCM that performed differently from CCSM would have been a reasonable choice for providing a second set of boundary conditions. As illustrated by our results below, the outcome of the RCM simulations, including the sign of projected change, are critically dependent on this choice. An evaluation of RegCM3 forced with both reanalysis and CCSM can be found in *Walker and Diffenbaugh* [2009], *Diffenbaugh and Ashfaq* [2010], and *Diffenbaugh et al*. [2011]. An evaluation of RegCM3 forced with reanalysis and ECHAM can be found in *Winter and Eltahir* [2012].

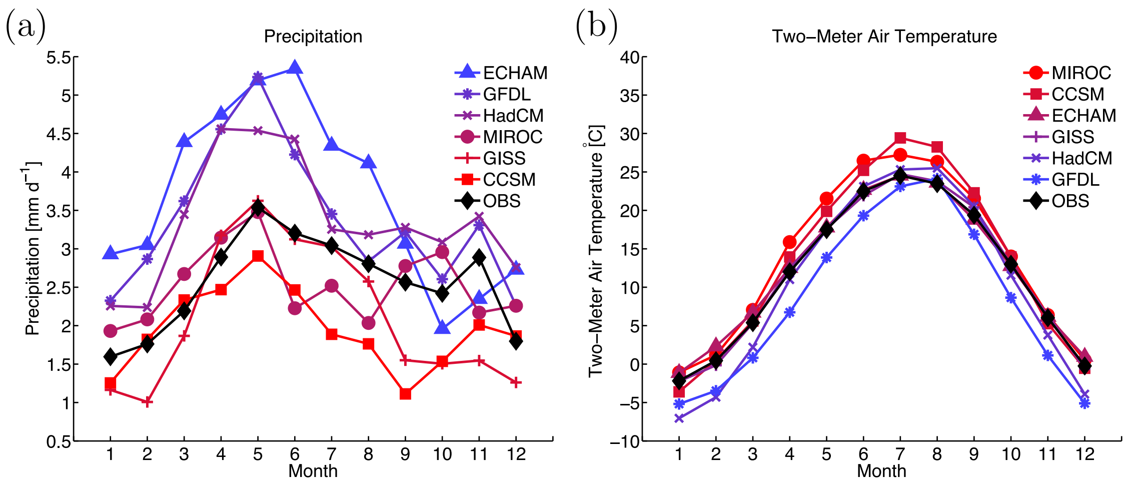

Figure 1. Simulated historical and observed seasonal cycles of precipitation and surface temperature. Seasonal cycles (1984–2005) of: (a) precipitation and (b) 2 m air temperature from National Center for Atmospheric Research CCSM3; Max Planck Institute for Meteorology ECHAM5; NOAA Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1; NASA Goddard Institute for Space Studies GISS-ER; The University of Tokyo, National Institute for Environmental Studies, and Frontier Research Center for Global Change MIROC3.2; and Hadley Centre for Climate Prediction and Research and UK Met Office HadCM3 simulations and ISWS and University of Delaware observations averaged over the box in Figure 3.

Figure 1 highlights the differences in the climate projected by GCMs over the American Midwest by showing the seasonal cycles of precipitation and surface temperature for six GCM simulations from CMIP3 and observations. ECHAM simulates too much precipitation during the growing season and overestimates the seasonal variability of precipitation. CCSM underestimates precipitation for most months, but roughly captures the shape of the observed precipitation seasonal cycle. ECHAM accurately simulates surface temperature for most of the year, with a slight overestimation of surface temperature in the winter. CCSM simulates a warm bias from April to September, but approximately reproduces observed surface temperature in the winter. It is important to caveat that because the RCM simulations conducted use boundary conditions with distinct biases, they are unlikely to produce the most accurate projections of future climate. However, using multiple sets of boundary conditions does enable an assessment of the sensitivity of simulated changes in the American Midwest hydrologic cycle to large-scale forcing not possible with regional climate modeling studies that only consider one driving GCM.

Historical simulations were initialized 1 April 1982, allowed to spin-up for 21 months, and 1984–2005 were analyzed. Future simulations were initialized 1 April 2076, allowed to spin-up for 21 months, and 2078–2099 were analyzed. GCM simulations for the future time period were driven by the A1B emissions scenario. The domain for all experiments was 100 points zonally by 60 points meridionally at 60 km resolution, centered over 40°N, 95°W.

To assess historical trends in the hydroclimatology of the American Midwest, one of the most comprehensive regional hydrologic cycle data sets in the world was evaluated. Monthly time series of precipitation, root zone soil moisture, and groundwater level; streamflow; and surface temperature were provided by ISWS, US Geological Survey (USGS), and University of Delaware, respectively, for 1984–2009 (root zone soil moisture 1985–2009). The precipitation time series was constructed from an average of 117 ISWS stations. The root zone soil moisture time series was derived from 15 Illinois Climate Network (ICN) meteorological stations where weekly to biweekly neutron probe soil moisture measurements were collected by ISWS for the entire 1985–2009 period [*Hollinger and Isard*, 1994; *Yeh et al*., 1998]. Groundwater level measurements were also provided by ISWS, and sampled 10 wells with a complete record for 1984–2009. Wells were located far away from pumping centers and streams to ensure fluctuations in groundwater level primarily reflect climate and not human (e.g., pumping, water withdrawal, and urbanization) influences. Water table level is negative for consistency with other variables. The streamflow time series consists of USGS daily discharge measurements from the three largest basins in Illinois: Illinois River at Valley City, Rock River near Joslin, and Kaskaskia River near Venedy. The total drainage area of these basins covers approximately two thirds of the state. Discharges were weighted by drainage area and averaged by month. Additional details about the construction of precipitation, streamflow, and groundwater level data can be found in *Yeh and*

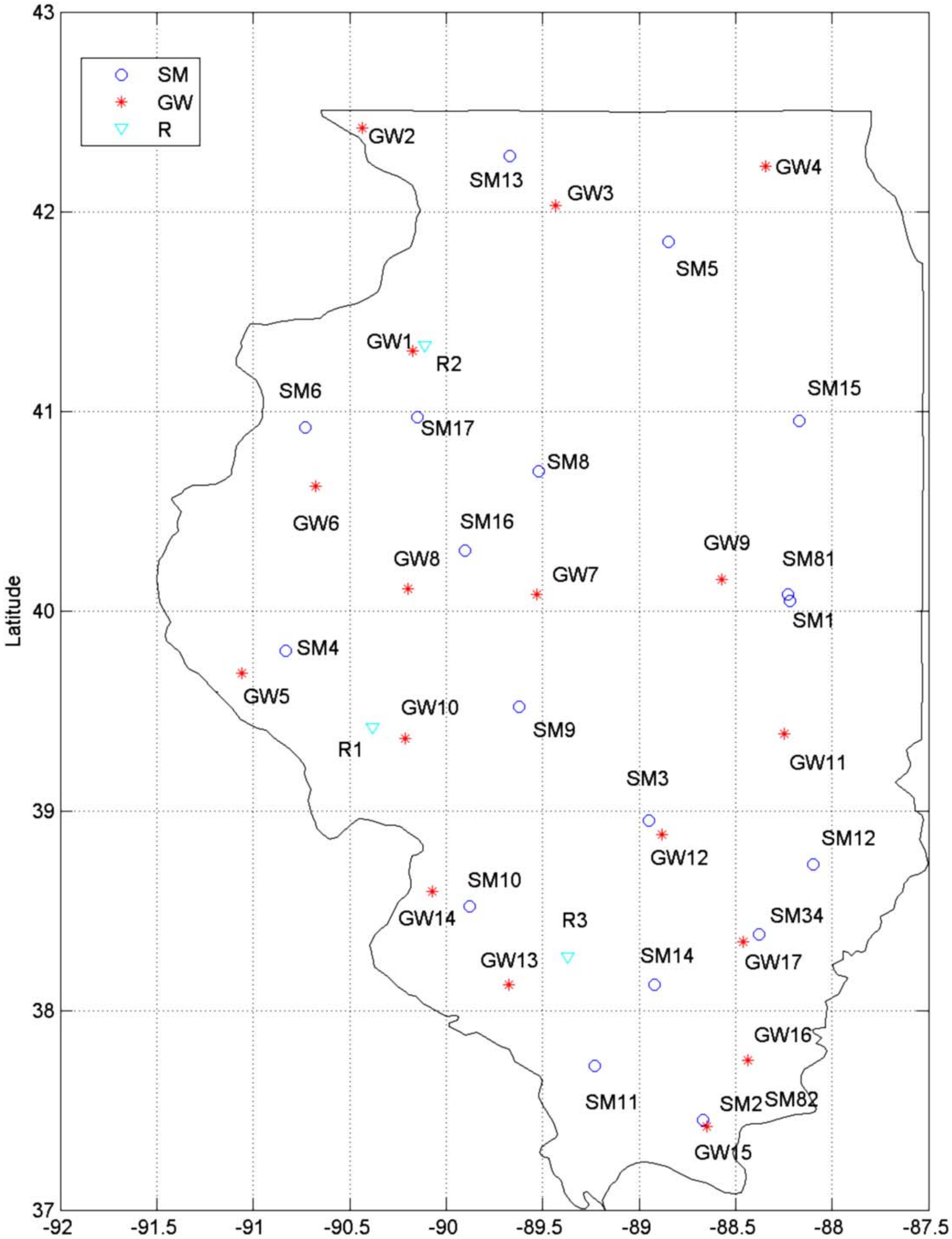

Figure 2. Illinois observational network. Locations of soil moisture (SM), groundwater level (GW), and streamflow (R) measurements.

Famiglietti [2008]. Locations of soil moisture, streamflow, and groundwater level observational measurements are shown in Figure 2. Surface temperature was computed using 0.5°× 0.5° University of Delaware Air Temperature and Precipitation Version 3.01 gridded data [*Willmott and Matsuura*, 2001] averaged over the box in Figure 3.

Anomalies were calculated by removing the 1984–2009 (root zone soil moisture 1985–2009) seasonal cycle from the 1984–2009 (root zone soil moisture 1985–2009) monthly time series. The Mann-Kendall test was calculated using the monthly anomalies described above normalized by the standard deviation of the

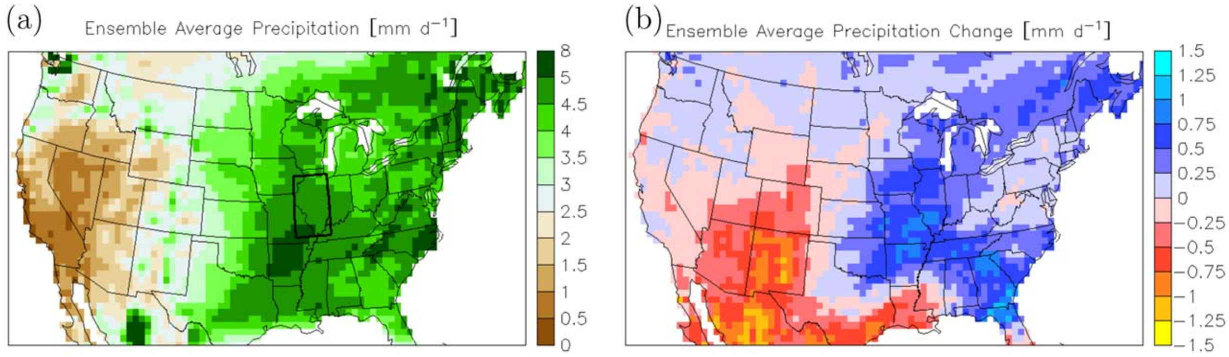

Figure 3. Simulated growing season historical precipitation and future precipitation change. Ensemble averaged growing season (April, May, June, July, August) of: (a) precipitation for the historical period (1984–2005) and (b) change between future (2078–2099) and historical (1984–2005) precipitation. The 4.0° $\times$ 5.5° black box shows the extent of spatial averaging for Figures 1, 4, and 5.

1984–2009 (root zone soil moisture 1985–2009) seasonal cycle; a 1984–2009 (root zone soil moisture 1985–2009) seasonal time series minus the 1984–2009 (root zone soil moisture 1985–2009) seasonal average for spring (March, April, May), summer (June, July, August), fall (September, October, November), and winter (December, January, February); and the 1984–2009 (root zone soil moisture 1985–2009) annual time series minus the 1984–2009 (root zone soil moisture 1985–2009) annual average. Because data are not available for December 1983, the winter seasonal time series contains one less value.

3. Results

An assessment of simulated and observed historical changes in, as well as regional climate model projections of, the American Midwest hydrologic cycle is described below.

3.1. Modeling Analysis

Figure 3 presents the growing season (April, May, June, July, August) ensemble average of precipitation for the historical time period and the change in the growing season ensemble average of precipitation between the future and historical time period. Figure 3 shows the domain of RCM simulations cropped by six points on each side to eliminate edge effects and the 4.0°$\times$ 5.5° black box in Figure 3 centered over the state of Illinois shows the spatial extent of averaging for the regional analyses presented below. This area was chosen for maximum overlap with observational data sets. Averaged across the RCM ensemble, climate change generally enhances precipitation over wet areas and reduces precipitation over dry areas. While precipitation changes in the Northeast are small, larger increases across the Midwest and Southeast are likely to diminish drought conditions, but have the potential to cause additional floods. The Southwest and southern Texas, areas that are already water stressed, are projected to experience decreased precipitation and an increased likelihood of drought conditions, a finding consistent with previous work [*Melillo et al*., 2014; *Diffenbaugh et al*., 2008].

Figures 4 and 5 present simulated historical seasonal cycles of precipitation, root zone soil moisture, surface temperature, evapotranspiration, and total runoff for the RCM ensemble, and differences between future (2078–2099) and historical (1984–2005) seasonal cycles, with ensemble members colored based on GCM forcing. Crosses denote nonoverlapping 95% confidence intervals between future and historical seasonal cycles. A striking result of Figure 4 is the influence of lateral boundary conditions, dictated by our choice of GCMs, on historical seasonal cycles. In some cases, the RCM seems to ameliorate biases in the GCM (e.g., winter precipitation in the ECHAM-driven simulations), while in others it exacerbates (e.g., CCSM-driven summer surface temperature). Differences between future and historical seasonal cycles of precipitation also depend on boundary conditions, where ensemble members forced by CCSM became drier and ensemble members forced by ECHAM became wetter. There is a significant precipitation increase during late spring and early summer in most of the ECHAM-driven simulations. There is also one significant decrease in precipitation during the month of July in a CCSM-driven ensemble member. These changes in precipitation under a warmer climate cascade through the hydrologic cycle. Increased precipitation in ECHAM-driven simulations increases

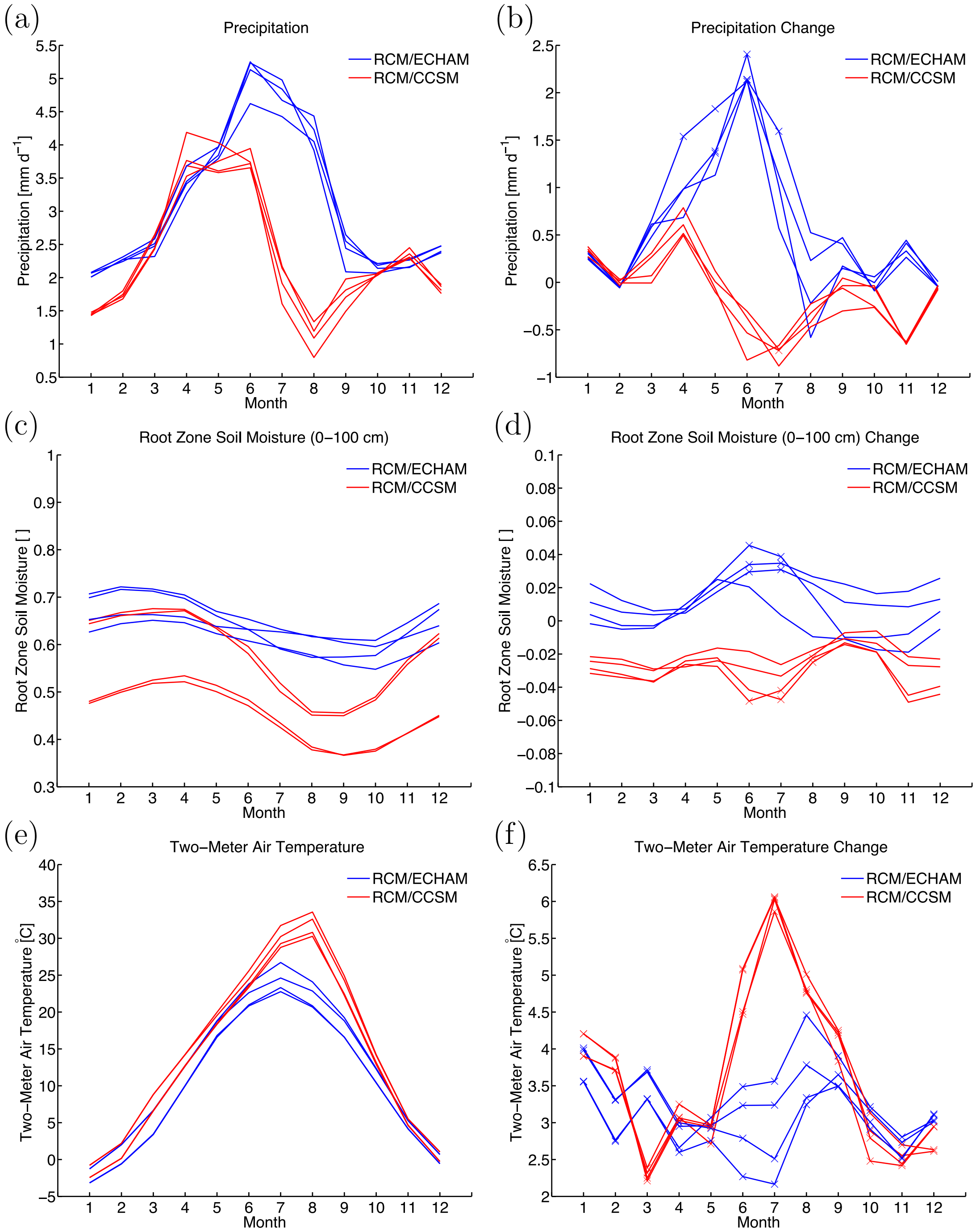

Figure 4. Simulated historical seasonal cycles and future changes in seasonal cycles of precipitation, soil moisture, and surface temperature. RCM historical (1984–2005) seasonal cycles of: (a) precipitation, (c) root zone soil moisture, and (e) 2 m air temperature averaged over the box in Figure 3. Differences between RCM future (2078–2099) and historical (1984–2005) seasonal cycles of: (b) precipitation, (d) root zone soil moisture, and (f) 2 m air temperature averaged over the box in Figure 3. Crosses denote nonoverlapping 95% confidence intervals between future and historical seasonal cycles. Line color denotes lateral boundary condition; convective parameterization (FC, AS) and land surface scheme (IBIS, BATS) are not differentiated.

runoff and to a lesser extent evapotranspiration, suggesting that evapotranspiration is largely not water limited and soil moisture accumulation enhances total runoff. In contrast, the decrease of precipitation in CCSM-driven simulations primarily decreases evapotranspiration in July and August as reduced precipitation in these months shifts the evapotranspiration seasonal cycle earlier in the year. Overall, differences between future

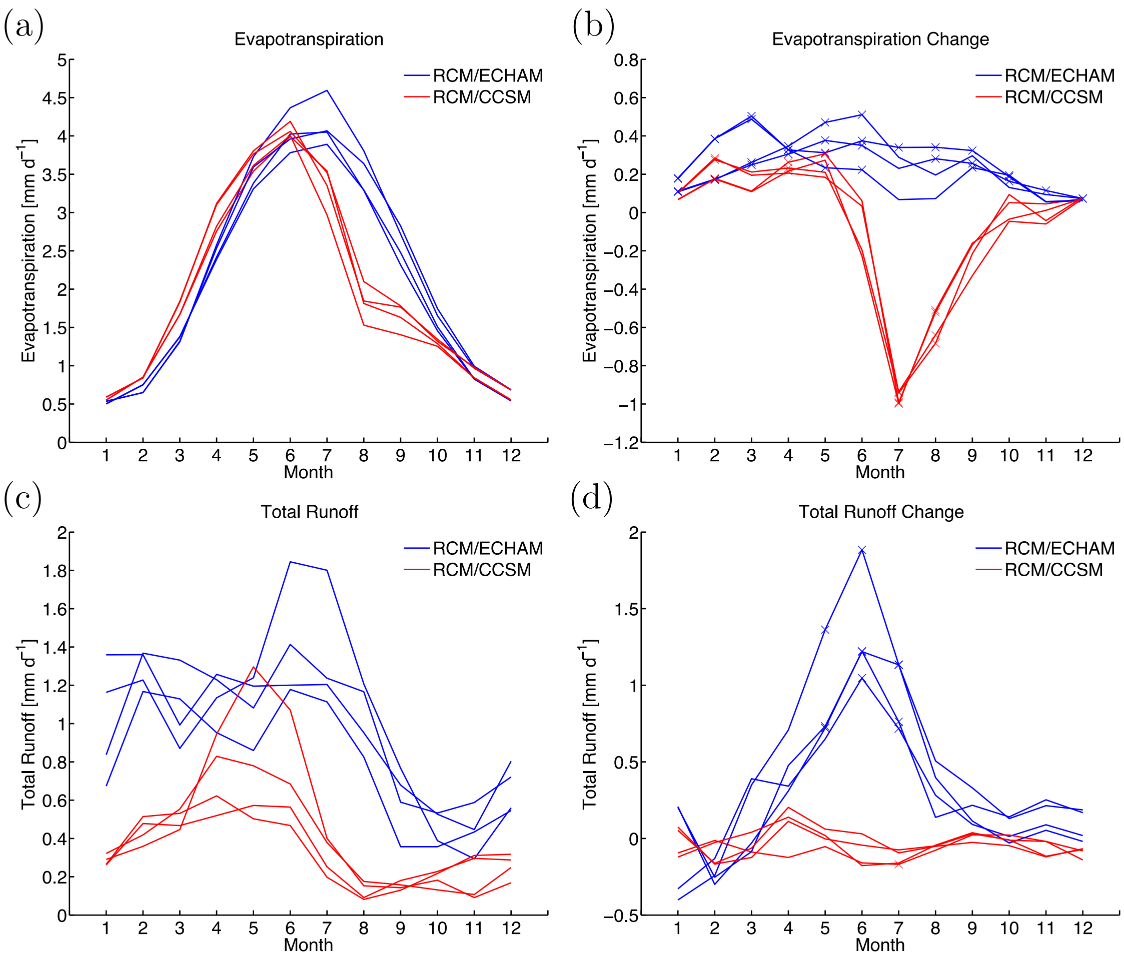

Figure 5. Simulated historical seasonal cycles and future changes in seasonal cycles of evapotranspiration and total runoff. RCM historical (1984–2005) seasonal cycles of: (a) evapotranspiration and (c) total runoff averaged over the box in Figure 3. Differences between RCM future (2078–2099) and historical (1984–2005) seasonal cycles of: (b) evapotranspiration and (d) total runoff averaged over the box in Figure 3. Crosses denote nonoverlapping 95% confidence intervals between future and historical seasonal cycles. Line color denotes lateral boundary condition; convective parameterization (FC, AS) and land surface scheme (IBIS, BATS) are not differentiated.

and historical seasonal cycles of root zone soil moisture are relatively small compared to seasonal variability and depend on large-scale forcing. However, some individual ensemble members do contain significant changes in summer soil moisture, with CCSM-driven simulations becoming more dry and ECHAM-driven simulations becoming more wet. Future growing season surface temperature is significantly warmer than historical growing season surface temperature throughout the year in all ensemble members. CCSM-driven simulations project a substantially greater surface temperature increase during summer months that is coincident with reduced precipitation and evapotranspiration.

While lateral boundary conditions clearly have the greatest influence on the ensemble, some hydrologic variables are also influenced by convective parameterization and land surface scheme. Historical seasonal cycles of root zone soil moisture simulated using BATS are consistently drier than those simulated using IBIS, a result that is especially noticeable in the CCSM-driven simulations, and simulations using IBIS tend to produce more runoff over the historical period (not shown). The effect of convective parameterization and land surface scheme on changes to the hydrologic cycle under future climate is less clear; however, in general the reduction of soil moisture is greater in IBIS simulations than in BATS simulations (not shown).

The range of summer soil moisture response to future climate is largely consistent with previous studies of climate change impacts on the hydrologic cycle of the American Midwest. CCSM-driven simulations replicate the drying found by *Diffenbaugh and Ashfaq* [2010], who also used CCSM simulations as boundary conditions. However, ECHAM-driven simulations produce no change or soil moisture increases. This agrees with

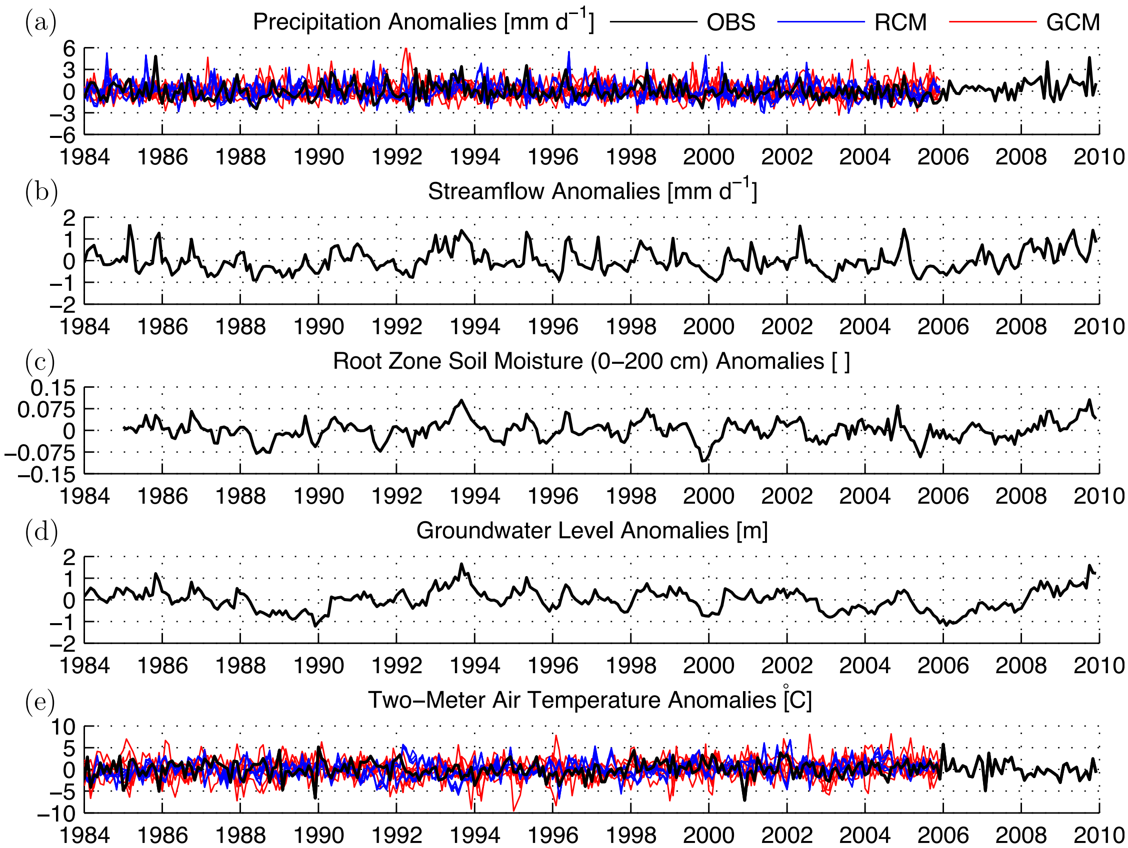

Figure 6. Observed (1984–2009, root zone soil moisture 1985–2009) anomaly time series of: (a) precipitation, (b) streamflow, (c) root zone soil moisture, (d) groundwater level, and (e) 2 m air temperature; simulated (1984–2005) anomaly time series of: (a) precipitation and (e) 2 m air temperature for Illinois.

Seneviratne et al. [2002], who developed boundary conditions based on a fixed increase in temperature throughout the atmosphere, unchanged relative humidity, and enhanced CO_2, and *Mishra et al*. [2010], who created boundary conditions for VIC by bias correcting projections from three GCMs that had performed favorably over the Midwestern United States in past studies. Drying in CCSM-driven simulations is compatible with *Patricola and Cook* [2012], who found reduced precipitation (changes in soil moisture were not assessed) over the American Midwest during summer using the Weather Research and Forecasting Model driven by boundary conditions derived from an ensemble average of six GCMs that were selected for their ability to reproduce historical precipitation metrics and then bias corrected. However, changes in summer precipitation from a broader ensemble of GCMs and RCMs also evaluated by *Patricola and Cook* [2012] were ambiguous. We note that future soil moisture decreases are projected by simulations forced with CCSM, which has a dry bias over the historical period, while future soil moisture increases are projected by simulations forced with ECHAM, which has a wet bias over the historical period.

3.2. Observational Analysis

Figures 1, 4, and 5 provide evidence that regional predictions of climate change are uncertain and strongly influenced by large-scale forcing and sometimes parameterization scheme. Having established that our RCM simulations are not conclusive in their projections of American Midwest hydrology, we turn our attention to an extensive set of observations in Illinois. Given the large increase in greenhouse gas concentrations over recent decades, we assess the observed hydroclimatology of Illinois to determine if a discernible climate change signal exists that could inform the conflicting and relatively small changes in simulated soil moisture.

Figure 6 displays observed monthly time series of anomalies for components of the hydrologic cycle and surface temperature, as well as simulated monthly time series of anomalies for precipitation and surface temperature. Monotonic trends in all monthly, seasonal, and annual anomaly time series were evaluated

Table 1. Observed Kendall τ Coefficients for Precipitation, Streamflow, Root Zone Soil Moisture, Groundwater Level, and Surface Temperature (1984–2009, Root Zone Soil Moisture 1985–2009); Simulated Kendall τ Coefficients for Precipitation and Surface Temperature (1984–2005)[a]

	Monthly	Spring	Summer	Fall	Winter	Annual
Observed precipitation	0.06	0.18	0.27	−0.16	0.01	0.15
Observed streamflow	0.05	0.07	0.11	−0.05	0	0.03
Observed root zone soil moisture	0.02	0.07	0.02	0.11	−0.09	0.05
Observed water table level	−0.06	−0.06	0.05	−0.06	−0.22	−0.11
Observed 2 m temperature	−0.02	−0.02	−0.15	0.08	0.09	0
ECHAM IBIS AS74 precipitation	−0.06	−0.26	−0.11	−0.15	−0.03	−0.22
ECHAM IBIS FC80 precipitation	−0.06	−0.18	−0.31*	−0.19	−0.01	−0.27
ECHAM BATS AS74 precipitation	−0.07	−0.21	−0.06	−0.2	−0.04	−0.31*
ECHAM BATS FC80 precipitation	−0.07	−0.21	−0.25	−0.17	−0.01	−0.24
CCSM IBIS AS74 precipitation	0.01	0.16	−0.26	−0.13	0.25	0.09
CCSM IBIS FC80 precipitation	−0.03	−0.01	−0.25	−0.17	0.21	−0.09
CCSM BATS AS74 precipitation	0.01	0.08	−0.19	−0.06	0.17	0.04
CCSM BATS FC80 precipitation	0.02	0.11	−0.25	−0.07	0.16	0.02
ECHAM precipitation	0.04	0.14	0.01	0.03	0.24	0
CCSM precipitation	−0.02	−0.1	0.13	0.13	−0.4*	0.03
GFDL precipitation	−0.04	−0.04	−0.13	−0.08	0	−0.14
GISS precipitation	−0.03	−0.17	−0.06	−0.03	0.05	−0.02
MIROC precipitation	0.01	0.03	0.25	−0.19	−0.12	0.06
HadCM precipitation	0.07	0.01	0.13	0.21	0.17	0.13
ECHAM IBIS AS74 2 m temperature	0.1*	0.1	0.21	0.4*	−0.11	0.26
ECHAM IBIS FC80 2 m temperature	0.12*	0.11	0.16	0.5*	−0.1	0.31*
ECHAM BATS AS74 2 m temperature	0.1*	0.14	0.12	0.42*	−0.1	−0.25
ECHAM BATS FC80 2 m temperature	0.12*	0.15	0.17	0.49*	−0.09	0.26
CCSM IBIS AS74 2 m temperature	0.14*	0.2	0.36*	0.12	0.16	0.33*
CCSM IBIS FC80 2 m temperature	0.16*	0.23	0.38*	0.09	0.16	0.39*
CCSM BATS AS74 2 m temperature	0.14*	0.26	0.37*	0.06	0.21	0.39*
CCSM BATS FC80 2 m temperature	0.16*	0.23	0.47*	0.05	0.2	0.39*
ECHAM 2 m temperature	0.12*	0.21	0.36*	0.06	0.2	0.32*
CCSM 2 m temperature	0.13*	0.42*	0.09	0.03	0.2	0.43*
GFDL 2 m temperature	0.13*	0.25	0.41*	0.19	0.01	0.39*
GISS 2 m temperature	0.12*	−0.03	0.39*	0.13	0.21	0.21
MIROC 2 m temperature	0.06	0.12	0.13	0.22	0	0.13
HadCM 2 m temperature	−0.06	−0.01	0	−0.09	−0.15	−0.15

[a]An asterisk denotes a significant trend at a 95% confidence level.

using the Mann-Kendall test. No significant trends at a 95% confidence level are found for any observed variables, with the Kendall τ coefficients for precipitation, streamflow, root zone soil moisture, groundwater level, and surface temperature being 0.06, 0.05, 0.02, −0.06, and −0.02, respectively Table 1. Insignificant observed trends include enhanced precipitation annually and in each season except fall, warming in fall and winter, and cooling in summer. The absence of significant surface temperature warming in the American Midwest agrees with *Pan et al*. [2004] and *Kunkel et al*. [2006], but the lack of increasing precipitation is counter to longer term trends found by *Groisman et al*. [2004]. The majority of simulated precipitation trends are insignificant, consistent with observed precipitation trends, and largely negative especially in summer and fall. However, monthly trends in 2 m air temperature are significantly positive across all RCM and four GCM simulations including CCSM and ECHAM, highlighting the inability of most simulations to capture the absence of surface temperature warming in the American Midwest. Seasonally, in CCSM-driven simulations the surface temperature trend is significant in summer months, but in ECHAM-driven simulations the surface temperature trend is significant in fall months. While CCSM and ECHAM GCM simulations contain the same significant monthly warming trend as RCM simulations, the significant seasonal warming trend in the CCSM and ECHAM GCM simulations occurs one season in advance of the significant seasonal warming trend in the CCSM-driven and ECHAM-driven RCM simulations, respectively.

4. Discussion

Across Figures 1, 4, 5, and 6, several interesting findings emerge. Figures 4 and 5 show two sets of simulations that are distinguished by boundary conditions used. This sensitivity of RCMs to large-scale forcing is consistent with results from previous studies [*Wu et al*., 2005; *Kjellström et al*., 2011], and suggests that to increase the accuracy of regional climate model projections, RCM ensembles should emphasize choice of large-scale forcings over parameterization schemes. This also suggests that to sample across the range of possible regional climate futures, RCM ensembles should emphasize diversity of large-scale forcings.

Regional climate model simulations capture the surface temperature seasonal cycle well compared to observations over the American Midwest, and predict a clear increase in 2 m air temperature under climate change. This agreement of model projections suggests that adaptation to increased surface temperature should be given priority as the signal is robust and could have large impacts on crop yields [*Schlenker and Roberts*, 2009]. While future warming simulated by the RCMs is consistent with studies focused on both the Midwest [*Liang et al*., 2006] and broader United States [*Melillo et al*., 2014], it is important to caveat that most all GCMs and RCMs evaluated in this study, the exceptions being MIROC and HadCM, simulate a positive monotonic trend in 2 m air temperature over the past 26 years that is not found in the observations. *Liang et al*. [2006] noted that both the RCM and GCM used in their analysis projected increased surface temperature across the Central US by midcentury, with the GCM likely overestimating warming because it failed to simulate critical climate dynamics in the region. In contrast, the RCMs disagree on the sign of soil moisture change and the differences between historical RCM and observed soil moisture are much larger than differences between future and historical RCM simulations of soil moisture found by *Winter and Eltahir* [2012]. While some RCM ensemble members simulate significant summer soil moisture wetting or drying under future climate, the sign of this change depends primarily on boundary conditions. We caveat that the GCM boundary conditions used in this study were not chosen for their ability to simulate the observed seasonal cycles of temperature and precipitation over the American Midwest nor to be representative of the broader ensemble of CMIP3 projections over the American Midwest, rather they were selected to compare to *Diffenbaugh and Ashfaq* [2010] and then offer a counter example. CCSM and ECHAM simulate substantially different seasonal cycles of surface temperature and precipitation over the historical period, and it is expected that if GCM boundary conditions with similar seasonal cycles of surface temperature and precipitation were used the differences in future soil moisture simulated would be smaller.

Observations of recent climate variability over Illinois show no significant monotonic trends in soil moisture, precipitation, streamflow, groundwater level, or surface temperature. These observations span 26 years (root zone soil moisture 25 years), a period marked by a large increase in the concentration of greenhouse gases and substantial warming in the observed global surface temperature record [*Hansen et al*., 2010]. The lack of significant trends in the observed water cycle of the American Midwest supports the hypothesis that hydrologic variables and surface temperature over this region are not as sensitive to global climate change as some previous studies suggest. It remains to be seen if this lack of sensitivity will continue into the future as the magnitude of the radiative forcing from greenhouse gases increases.

Based on our ensemble of modeling results and analysis of recent observations, we conclude that the sign of climate change impacts on the hydrologic cycle over the American Midwest remains uncertain. The disagreement among models highlights the need for expanded observations of soil moisture and further analyses of simulated soil moisture in GCMs and RCMs to reduce modeling errors in projections of the hydrologic cycle, as well as the use of ensemble-based methods of regional climate modeling, such as the North American Regional Climate Change Assessment Program [*Mearns et al*., 2009] and Coordinated Regional Climate Downscaling Experiment [*Giorgi et al*., 2009], to capture the full range of potential responses of the hydrologic cycle to climate change.

Acknowledgments
We thank the Eltahir Group and the International Centre for Theoretical Physics for assistance and support, as well as our editor, associate editor, and reviewers for their thoughtful feedback. Jeremy Pal and Marc Marcella provided valuable contributions during model development and analysis. This work was funded by the National Science Foundation. Data can be obtained by contacting the corresponding author.

References

Alston, J., B. Babcock, and P. Pardey (Eds.) (2010), *The Shifting Patterns of Agricultural Production and Productivity Worldwide*, Midwest Agribusiness Trade Res. and Inf. Cent., Iowa State Univ. Ames, IA, USA.

Diffenbaugh, N. S., and M. Ashfaq (2010), Intensification of hot extremes in the United States, *Geophys. Res. Lett.*, *37*, L15701, doi:10.1029/2010GL043888.

Diffenbaugh, N. S., F. Giorgi, and J. S. Pal (2008), Climate change hotspots in the United States, *Geophys. Res. Lett.*, *35*, L16709, doi:10.1029/2008GL035075.

Diffenbaugh, N. S., M. Ashfaq, and M. Scherer (2011), Transient regional climate change: Analysis of the summer climate response in a high-resolution, century-scale ensemble experiment over the continental United States, *J. Geophys. Res.*, *116*, D24111, doi:10.1029/2011JD016458.

D'Odorico, P., and A. Porporato (2004), Preferential states in soil moisture and climate dynamics, *Proc. Natl. Acad. Sci. U. S. A.*, *101*(24), 8848–8851.

Findell, K. L., and E. A. B. Eltahir (1997), An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois, *Water Resour. Res.*, *33*, 725–735.

Fritsch, J. M., and C. F. Chappell (1980), Numerical prediction of convectively driven mesoscale pressure systems. Part I: Convective parameterizations, *J. Atmos. Sci.*, *37*, 1722–1733.

Giorgi, F., et al. (2009), Addressing climate information needs at the regional level: The CORDEX framework, *World Meteorol. Organ. Bull.*, *58*(3), 175–183.

Grell, G. A., J. Dudhia, and D. Stauffer (1994), A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5), *Tech. Note TN-398+IA*, Natl. Cent. for Atmos. Res., Boulder, Colo.

Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore (2004), Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations, *J. Hydrometeorol.*, *5*, 64–85.

Hall, A., and X. Qu (2006), Using the current seasonal cycle to constrain snow albedo feedback in future climate change, *Geophys. Res. Lett.*, *33*, L030502, doi:10.1029/2005GL025127.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, *Rev. Geophys.*, *48*, RG4004, doi:10.1029/2010RG000345.

Hollinger, S., and S. Isard (1994), A soil moisture climatology of Illinois, *J. Clim.*, *7*(5), 822–833.

Kjellström, E., G. Nikulin, U. Hansson, G. Strandberg, and A. Ullerstig (2011), 21st century changes in the European climate: Uncertainties derived from an ensemble of regional climate model simulations, *Tellus Ser. A*, *63*(1), 24–40.

Kochendorfer, J., and J. Ramirez (2005), The impact of land-atmosphere interactions on the temporal variability of soil moisture at the regional scale, *J. Hydrometeorol.*, *6*(1), 53–67.

Kunkel, K. E., X.-Z. Liang, J. Zhu, and Y. Lin (2006), Can CGCMs simulate the twentieth-century ''warming hole'' in the central United States?, *J. Clim.*, *19*(17), 4137–4153.

Liang, X.-Z., J. Pan, J. Zhu, K. E. Kunkel, J. X. L. Wang, and A. Dai (2006), Regional climate model downscaling of the U.S. summer climate and future change, *J. Geophys. Res.*, *111*, D10108, doi:10.1029/2005JD006685.

Lott, N., and T. Ross (2006), Tracking and evaluating U.S. billion dollar weather disasters, 1980–2005, Natl. Clim. Data Cent. Ashville, N. C. [Available at http://www1.ncdc.noaa.gov/pub/data/papers/200686ams1.2nlfree.pdf.]

Manabe, S., R. T. Wetherald, P. C. D. Milly, T. L. Delworth, and R. J. Stouffer (2004), Century-scale changes in water availability: CO_2 quadrupling experiment, *Clim. Change*, *64*, 59–76.

Mearns, L., W. Gutowski, R. Jones, R. Leung, S. McGinnis, A. Nunes, and Y. Qian (2009), North American Regional Climate Change Assessment Program: An overview, *EOS Trans. AGU*, *90*(36), 311.

Mearns, L., et al. (2013), Climate change projections of the North American Regional Climate Change Assessment Program (NARCCAP), *Clim. Change*, *120*(4), 965–975.

Melillo, J. M., T. Richmond, and G. Yohe (Eds.) (2014), *Climate Change Impacts in the United States: The Third National Climate Assessment*, U.S. Global Change Res. Program., Washington, D. C.

Mishra, V., K. A. Cherkauer, and S. Shukla (2010), Assessment of drought due to historic climate variability and projected future climate change in the Midwestern United States, *J. Hydrometeorol.*, *11*(1), 46–68.

Pal, J. S., et al. (2007), Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET, *Bull. Am. Meteorol. Soc.*, *88*, 1395–1409.

Pan, Z., R. W. Arritt, E. S. Takle, W. J. Gutowski, C. J. Anderson, and M. Segal (2004), Altered hydrologic feedback in a warming climate introduces a ''warming hole,'' *Geophys. Res. Lett.*, *31*, L17109, doi:10.1029/2004GL020528.

Patricola, C. M., and K. H. Cook (2012), Mid-twenty-first century warm season climate change in the Central United States. Part I: Regional and global model predictions, *Clim. Dyn.*, *40*, 551–568.

Quesada, B., R. Vautard, P. Yiou, M. Hirschi, and S. I. Seneviratne (2012), Asymmetric European summer heat predictability from wet and dry southern winters and springs, *Nat. Clim. Change*, *2*(10), 736–741.

Salvucci, G., J. Saleem, and R. Kaufmann (2002), Investigating soil moisture feedbacks on precipitation with tests of Granger causality, *Adv. Water Resour.*, *25*(8), 1305–1312.

Schlenker, W., and M. J. Roberts (2009), Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(37), 15,594–15,598.

Seneviratne, S. I., J. S. Pal, E. A. B. Eltahir, and C. Schär (2002), Summer dryness in a warmer climate: A process study with a regional climate model, *Clim. Dyn.*, *20*, 69–85.

Sheffield, J., and E. F. Wood (2008), Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations, *Clim. Dyn.*, *31*(1), 79–105.

Stegehuis, A. I., A. J. Teuling, P. Ciais, R. Vautard, and M. Jung (2013), Future European temperature change uncertainties reduced by using land heat flux observations, *Geophys. Res. Lett.*, *40*(10), 2242–2245, doi:10.1002/grl.50404.

Stocker, T., D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley (Eds.) (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press. Cambridge, U. K., and N. Y.

Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert (2010), Characterizing changes in drought risk for the United States from climate change, *Environ. Res. Lett.*, *5*(4), 044012.

Teuling, A., R. Uijlenhoet, and P. Troch (2005), On bimodality in warm season soil moisture observations, *Geophys. Res. Lett.*, *32*, L13402, doi:10.1029/2005GL023223.

Van der Linden, P., and J. Mitchell (Eds.) (2009), *ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project*, Met Off. Hadley Cent. Exeter, U. K.

Walker, M. D., and N. S. Diffenbaugh (2009), Evaluation of high-resolution simulations of daily-scale temperature and precipitation over the United States, *Clim. Dyn.*, *33*(7–8), 1131–1147.

Wang, G. (2005), Agricultural drought in a future climate: Results from 15 global climate models participating in the IPCC 4th assessment, *Clim. Dyn.*, *25*, 739–753.

Willmott, C., and K. Matsuura (2001), Terrestrial air temperature and precipitation: Monthly and annual climatologies (Version 3.02), Cent. for Clim. Res., Dep. of Geogr., Univ. of Delaware. Newark, DE, USA.

Winter, J. M., and E. A. B. Eltahir (2012), Modeling the hydroclimatology of the midwestern United States. Part 1: current climate, *Clim. Dyn.*, *38*(3-4), 573–593.

Winter, J. M., J. S. Pal, and E. A. B. Eltahir (2009), Coupling of integrated biosphere simulator to regional climate model version 3, *J. Clim.*, *22*, 2743–2757.

Wu, W., A. H. Lynch, and A. Rivers (2005), Estimating the uncertainty in a regional climate model related to initial and lateral boundary conditions, *J. Clim.*, *18*(7), 917–933.

Yeh, P. J. F., and J. S. Famiglietti (2008), Regional terrestrial water storage change and evapotranspiration from terrestrial and atmospheric water balance computations, *J. Geophys. Res.*, *113*, D09108, doi:10.1029/2007JD009045.
Yeh, P. J. F., and J. S. Famiglietti (2009), Regional groundwater evapotranspiration in Illinois, *J. Hydrometeorol.*, *10*, 464–478.
Yeh, P. J. F., M. Irizarry, and E. A. B. Eltahir (1998), Hydroclimatology of Illinois: A comparison of monthly evaporation estimates based on atmospheric water and soil water balance, *J. Geophys. Res.*, *103*, 19,823–19,837.